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Compensation of deterioration in microwave properties of GaInAs DDD due to mobile space charge and optical injection through modulation of impurity doping

S P Pati*, S K Dash[1] and K Mishra[2]

Department of Physics, Sambalpur University, Jyoti Vihar, Burla, Sambalpur-768 019, Orissa, India

[1]Department of Physics, Govt. Women's College, Sambalpur, Orissa, India

[2]Department of Physics, UCE, Burla, Sambalpur, Orissa, India

E-mail : patispsu@sancharnet.in

Abstract : GaInAs double drift diode (DDD) operating in the IMPATT mode has been designed and analyzed for several frequency bands of operation under varying operating conditions to study its microwave properties. The microwave performance characteristics show rapid deterioration when operating current density is increased (due to mobile space charge) and with the decrease of multiplication factor (due to optical injection and increase of saturation current). The authors have devised a technique to compensate the deteriorating effects of both the factors through modulation of flat doping concentration of GaInAs diode.

Keywords : IMPATT Diode, double drift diode, optical injection.

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1. Introduction

The IMPATT (IMPact Ionization and Avalanche Transit Time) diode, which is a reversed biased *p-n* junction diode generates microwave and MM-wave power in the frequency range of 8 to 350 GHz. The physical processes that take place in IMPATT action are multiplication of charge carriers in avalanche zone and transit of charge carriers within the drift zone. The transit time delay along with avalanche phase delay produces appropriate conditions for realization of negative resistance at microwave frequencies which in turn would generate microwave oscillations.

The IMPATT action can be observed in any semiconductor *p-n* junction as the basic phenomena involved in such action are not typical of a particular semiconductor. The use of opto-sensitive materials like GaInAs for fabrication of IMPATT diodes is on the rise for application as APD (Avalanche Photo Diode) optical communication, and control of IMPATT properties by optical radiation.

The mechanism of optical control in an IMPATT diode is realized by illuminating the diode through the incidence of external ionizing radiation. The optical illumination varies the level of reverse saturation current, which alters the avalanche buildup of charge carriers, causing a further phase difference between the RF voltage and RF current. The optically generated electron-hole pairs together with the thermally generated electron-hole pairs increase the level of the saturation current. The multiplication factor which is an important determining parameter of the IMPATT diode operation is directly related to the total saturation current. The multiplication factor (M) of the IMPATT diode which is defined as the ratio of the total terminal current coming out (due to electron or hole) at the end of the *p-n* junction to the (electron or hole) saturation current entering the junction is taken to be infinite (10^6 for practical purpose) under normal IMPATT operating condition. In the presence of the optical illumination, the saturation current increases

*Corresponding Author

by orders of magnitude and thereby multiplication factor decreases. This decrease in the carrier multiplication factor reduces the RF power generation from the diode.

The RF power output from the device can be enhanced by increasing the operating bias current density *i.e.* by increasing the input power. However, the authors have observed that the device performance and noise generation deteriorate sharply when the bias current is increased beyond a level (twice the optimum operating current) due to avalanche expansion caused by heavy mobile space charge.

The authors have continued their studies to search for the method of compensation of deterioration effects by which the normal optimum characteristics of the diode can be restored even at heavy bias current density and in the presence of optical radiation. For this purpose the properties of GaInAs diode have been studied under optical radiation and with heavy bias current. It was noticed that the deteriorating effect due to optical injections and high current operation could be compensated by modulation of doping of the p or n zone of this junction.

2. Method

To obtain the complete DC, microwave and noise properties of the IMPATT diode, the authors have undertaken the static analysis (DC analysis), dynamic analysis (small signal analysis) and noise analysis, following the method indicated below.

DC analysis :

At first, the device is analysed by static analysis by the simultaneous solution of the Poisson's equation,

$$\frac{\partial E}{\partial x}=\left(\frac{q}{\epsilon}\right)(N_D-N_A+p-n) \tag{1}$$

and the carrier continuity equations

$$\frac{\partial n}{\partial t}=\left(\frac{1}{q}\right)\left(\frac{\partial Jn}{\partial x}\right)+(\alpha_n n v_n+\alpha_p p v_p)=0$$

$$\frac{\partial p}{\partial t}=\left(\frac{-1}{q}\right)\left(\frac{\partial Jp}{\partial x}\right)+(\alpha_n n v_n+\alpha_p p v_p)=0 \tag{2}$$

Defining $p(x) = (\{J_p(x) - J_n(x)\})/J_0$, the pairs of eq. (2) are transformed into

$$\frac{\partial p(x)}{\partial x}=(a_n+a_p)-(a_n-a_p)p(x)\,, \tag{3}$$

where E is electric field, q is electronic charge, e is permittivity, N_D (N_A) is donor (acceptor) doping concentration, $n(p)$ is electron (hole) concentration, J_n (J_p) is electron (hole) current a_n (a_p) is electron (hole) ionisation rate, J_0 is total current density and v_n (v_p) is electron (hole) velocity.

And space charge equation

$$\frac{q\partial(p-n)}{\partial x}=-q(\alpha_n-\alpha_p)(p-n)$$
$$J_0\left\{\left(\frac{\alpha_n}{v_p}\right)+\left(\frac{\alpha_p}{v_n}\right)\right\}+\left(\frac{\partial E}{\partial x}\right)K\,, \tag{4}$$

where the correction factor K is defined as,

$$K=(J_p)\frac{\partial}{\partial E}\left(\frac{1}{v_p}\right)-(J_n)\frac{\partial}{\partial E}\left(\frac{1}{v_n}\right)$$

Eqs. (1), (3) and (4) are solved taking usual boundary conditions into account in $J_{n,p}$ and $E(x)$ [1]. A very fast converging double iterative computer method has been framed to ensure accurate solution.

The DC field profile and carrier distribution profile for the particular IMPATT diode operating at a given current density are obtained from the final solution [1]. The solution also gives the avalanche zone width, the breakdown voltage (V_B), the voltage drop across the avalanche zone (V_A) and voltage drop across the drift zone (V_D). The device efficiency is also determined from the relation $h = V_D/pV_B$.

Small signal analysis :

The DC data obtained from DC analysis for the diode having a particular doping profile and operating condition are used as input for the small signal analysis. The analysis involves the simultaneous solution of two integrated second order differential equations in diode negative resistance (R) and reactance (X) [2,3] which are given as :

$$D^2R+(\alpha_n-\alpha_p)DR-\left(\frac{2r\omega}{\bar{v}}\right)DX$$
$$+\left\{\left(\frac{\omega^2}{\bar{v}^2}\right)-H(x)\right\}R-\left(\frac{2\bar{\alpha}\omega}{\bar{v}}\right)X=\frac{2\bar{\alpha}}{\bar{v}\varepsilon} \tag{5}$$

$$D^2X+(\alpha_n-\alpha_p)DX-\left(\frac{2r\omega}{\bar{v}}\right)DR$$
$$+\left\{\left(\frac{\omega^2}{\bar{v}^2}\right)-H(x)\right\}X-\left(\frac{2\bar{\alpha}\omega}{\bar{v}}\right)R$$
$$=-\omega(v^{-2}\varepsilon)^{-1} \tag{6}$$

where the quantities $\bar{v}, \bar{\alpha}$, r, D and H are defined as :

$$\bar{v}=(v_{sn}.v_{sp})^{1/2}, \qquad \bar{\alpha}=\frac{(\alpha_n v_{sn}+a_p v_{sp})}{2\bar{v}}$$

$$r=\frac{(v_{sn}-v_{sp})}{2\bar{v}}, \qquad D=\frac{\partial}{\partial x}$$

$$H(x)=\left(\frac{2J_0}{\bar{v}\varepsilon}\right)\left(\frac{\partial\bar{\alpha}}{\partial E}\right)+\left(\frac{\partial}{\partial E}\right)(\alpha_p-\alpha_n)D$$

Iterating over initial choice of initial values of R and X at the left hand edge, the boundary conditions are matched on the right hand edge to get the final solution. The final solution of the device equations gives RF properties and the spatial distribution of negative resistance R and reactance X. The integrated values of the resistance and reactance are obtained as,

$$Z_R = \int R(x)dx \quad \text{and} \quad Z_X = \int X(x)dx$$

The device negative conductance (G) and susceptance (B) are calculated using the relation,

$$G = Z_R/(Z_R^2 + Z_X^2), \quad B = -Z_X/(Z_R^2 + Z_X^2)$$

The small signal analysis also gives the band width and optimum frequency (f_p) at which the diode negative conductance ($-G_p$) passes through a peak.

Noise analysis :

The data which have been obtained from the DC analysis of the IMPATT diode are also used as input for the noise analysis. The noise generating source (g) is considered to be located at point $x¢$[4,5]. This noise source at $x¢$consequently would produce noise electric field along the entire length of the depletion layer. The fundamental device equations are framed and solved simultaneously with the noise generating source located at the point $x¢$ The two second order differential equations on the real and imaginary parts of the noise electric field e_R and e_X are solved subject to fulfilment of the usual boundary conditions [6] by taking the help of another double iterative computer method [4,7]. The noise generating source is initially considered to be located at the left edge of the active zone ($x_I¢$ when I = 1) and the values of e_R and e_X are calculated at each space step from the final solution. The integral value of $e_R(x, x¢)$ and $e_X(x, x¢)$ give the terminal voltage $V_R(x¢)$ and $V_X(x¢)$ respectively following the relation, $V_R(x¢) = ∫e_R(x, x¢)dx$ and $V_X(x¢) = ∫e_X(x, x¢)dx$. The method is repeated by shifting the location of noise source to $x_I¢$ with I taken as 2, 3, 4 ... *etc*. Thus noise generation and its distribution can be calculated for noise element located in different zones of the active layer of the diode. These values of the terminal voltages can be used to calculate the mean squared noise voltage $\langle V^2\rangle/df$ of the diode at operating frequency f_p through computation of the diode transfer impedance Z_T [4,6].

The method is made realistic and generalized by considering realistic impurity profile across the junction and incorporating realistic variation of ionization rates and drift velocities of GaInAs with electric field. The space width is taken to be 1 nm for the numerical analysis. All the three computer programs have been designed to give fast convergence.

3. Results and discussion

Opto-sensitive GaInAs flat profile double drift diodes have been designed for operation in V-band (50–75 GHz) and optimised to realise optimum punch through factor and low normalised avalanche zone (x_A/W) through several computer runs based on static analysis. The ionization rate constants data, the saturated drift velocity of electron and hole, their mobility and permittivity data in case of GaInAs have been enlisted in Table 1. The diode then was analysed to compute DC, RF and noise characteristics with values of bias current in the range of 10^8 A/m^2 (Optimised) to 2 × 10^9 A/m^2.

Table 1. Material parameter data of GaInAs

Ionization Rate Constants	A_n = 2.27 × 10^8/m
	b_n = 1.23 × 10^8 V/m
	A_p = 3.95 × 10^8/m
	b_p = 1.45 × 10^8 V/m
Saturated carrier	V_{sn} = 6.39 × 10^4 m/s
Drift velocity	V_{sp} = 6.39 × 10^4 m/s
Mobility	m_n = 0.79 m^2/V/s
	m_p = 0.025 m^2/V/s
Permittivity	e =1.20 × 10^{-10} F/m

The results have been presented in Table 2. It has been observed that the value of x_A/W expands from 45% at J = 10^8 A/m^2 to 90% at J = 10^9 A/m^2, which in turn results in the fall of device efficiency (h) from 13.6% to 0.8% for the same change in bias current density. The rapid avalanche expansion at high current density can be explained on the basis of the electric field profile. The electric field is observed to be triangular at the optimized current density. When the current density is increased to 10^9 A/m^2, the field profile is distorted and the field gradient reverses near the edges causing the electric field to rise again. This results in rapid impact ionisation over an elongated zone causing expansion in avalanche zone. This fact also causes the fall in diode negative resistance and enhancement of avalanche noise at high value of bias current density (Table 2).

Table 2. Device properties of the diode (M_n, M_p = 10^6), showing deterioration due to increase in current density

Current density ® J (10^8 A/m^2)	1.0	2.0	5.0	10.0
Device properties				
E_m, ´ 10^7 (V/m)	3.45	3.40	3.29	3.17
X_A/W (%)	45.2	51.3	78.9	90.1
h (%)	13.6	11.2	5.1	0.8
$-G_p$,10^6 S/m^2	13.4	18.9	21.6	22.4
$-Z_{Rp}$,10^{-9} Wm^2	16.2	14.4	11.1	9.8
f_p, GHz	60	74	132	160
$\langle V^2\rangle/df$, 10^{-18} V^{2}s	3.9	3.98	4.5	6.67

The diode then was analysed with multiplication factor $M_{n,p}$ in the range of 10^6 to 10 for each value of bias current density. The results further show degradation in device properties for low values of $M_{n,p}$ which corresponds to exposure of the diode to optical radiation of suitable frequency. The results are mentioned in Table 4. The device efficiency and the magnitude of diode negative resistance decrease further at $M_{n,p}$ equal to 10. Thus the diode which has been designed to be used as APD or a device for optical communication would produce low RF power when exposed to photon radiation. Any attempt to raise the power level by increasing the input current density (*i.e.* input power) would further degrade device performance due to avalanche expansion.

We have continued our studies to design a method to compensate the deterioration caused by optical radiation/bias current density, and observed that the same can be achieved by modulating the doping levels of *n-p* regions of the junction. The results are shown in Table 3 and Table 4.

Table 3. Compensation of device properties of the diode (M_n, M_p = 10^6) with modified doping.

Current density ® J (10^8 A/m^2)	1.0	2.0	5.0	10.0
Optimized Modified Doping of *n/p* ® $N_D = N_A$, 10^{22}/m^3	4.8	5.8	7.8	8.7
E_m, 10^7 V/m	3.44	3.42	3.44	3.43
h (%)	13.6	13.8	14.1	14.1
$-Z_{Rp}$, 10^{-9} W m^2	16.2	16.1	16.3	16.2
f_p, GHz	60	74	130	161
$<V^2>/df$, 10^{-18} V^{2}s	2.3	2.35	2.38	2.39

The results indicate that the doping level of *n-p* region should be suitably increased to get back the optimum performance. It is very interesting to see that the deteriorating effect due to both the factors could be totally compensated by this technique. When doping of *n* and *p* regions are increased to 8.7×10^{22}/m^3 for operation at $J = 10^9$ A/m^2 and $M_{n,p} = 10$, the device efficiency again increases from 0.8% to 14.1%.

Table 4. Device properties of the diode (M_n, M_p = 10) with unmodulated and modulated doping

Current density ® J (10^8 A/m^2)	1.0	5.0	5.0	10.0	10.0
Optimized Modified Doping		Unmod	Mod	UnMod	Mod
($N_D = N_A$ 10^{22}/m^3)	4.8	4.8	7.8	4.8	8.7
h (%)	12.6	4.2	13.9	0.7	14.0
$-Z_{Rp}$, 10^{-9} W m^2	15.8	12.1	16.0	9.25	15.95
$<V^2>/df$, 10^{-18} V^{2}s	3.85	4.6	3.87	6.61	3.92

The electrical field profile again becomes triangular even at 10^9 A/m^2 for the modulated diode with impurity doping of *n/p* regions equal to 8.7×10^{22}/m^3. Correspondingly, the device negative resistance is also enhanced and avalanche noise is reduced to the level corresponding to $J = 10^8$ A/m^2 and $M_{n,p} = 10^6$ for the modified DDD. Thus, the GaInAs diode can be used as an efficient APD and device in optical communication by operating it at high value of current density and simultaneously modifying the impurity level of *n* and *p* regions.

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